METHOD AND APPARATUS FOR NOISE REDUCTION USING DISCRETE WAVELET TRANSFORM

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10   <u>**Field of the invention**</u>

The present invention relates generally to image processing, and more particularly to noise reduction in images.

15   <u>**Background of the invention**</u>

Video images are often corrupted by noise in the acquisition or transmission process. In order to improve the visual appearance of the images, an effective filtering technique is often required to reduce the noise level. The

20 goal of the noise reduction is to remove the noise while retaining as much of important image features as possible.

Conventional noise reduction processes primarily involve linear processing in either spatial or spectrum

domain. However, while reducing noise by attenuating the

high frequency image components, linear processing removes

some important image details as well.

5   As such, there has been a trend in developing

nonlinear noise reduction processes. One such process is

wavelet thresholding. In the wavelet domain, important

image features are represented by large coefficients while

noise components are usually represented by

10 small/insignificant coefficients. Wavelet thresholding

provides a tool for separating noise signals from image

signals. The basic idea of the wavelet thresholding is

that noise can be removed by eliminating the insignificant

coefficients relative to some threshold value. Therefore,

15 in this approach, the discrete wavelet transform of an

image signal is calculated and the resultant wavelet

coefficients are threshold level tested. The coefficients

that are smaller than a certain threshold value are

removed. Then the resultant coefficients are used to

20 reconstruct the signal. If a signal has its energy

concentrated in a small number of wavelet coefficients, its

coefficient values will be relatively large compared to the

noise (which has its energy spread over a large number of

coefficients).

A crucial step in wavelet thresholding, is the selection of the threshold values. Improperly selected threshold values not only affect the performance of the

5 noise reduction process, but also create visually annoying artifacts. Although several attempts have been made in developing various methods of selecting threshold value, such selection methods have shortcomings in proper selection of threshold value, most of those methods were

10 targeting at denoising of highly noisy images. When they are applied to the applications that require good quality images, they often create noticeable artifacts.

Brief summary of the invention

15   An object of the present invention is to provide an improved noise reduction process by wavelet thresholding, that reduces noise level in video images and retains as much of the important image features as possible. In one embodiment, such an improved process first utilizes a

20 discrete wavelet transform to decompose the image into different resolution levels. Then, a thresholding function is applied in different resolution levels with different threshold values to eliminate insignificant wavelet coefficients which mainly correspond to the noise in the

original image. Finally, an inverse discrete wavelet

transform is applied to generate the noise-reduced video

image.

5   According to an aspect of the present invention, the

selection of the threshold values in the second step of the

noise reduction procedure above is based on the

relationships between the noise standard deviations of

different decomposition levels in the wavelet domain and

10 the noise standard deviation of the original image. In one

example, for any fixed discrete wavelet transform: (1) the

noise standard deviations of different decomposition levels

in the wavelet domain decrease as the decomposition levels

increase, and (2) the noise standard deviations in the

15 wavelet domain are linearly dependent on the noise standard

deviation of the original image. This linear dependency

provides a natural choice of the threshold values for

wavelet thresholding. For every discrete wavelet

transform, the noise standard deviations in the wavelet

20 domain have their unique linear dependency of the noise

standard deviation of the original image. Using this linear

dependency in wavelet thresholding is important in

producing artifacts free, natural looking de-noised image,

according to the present invention.

Other objects, features and advantages of the

invention will be apparent from the following specification

taken in conjunction with the following drawings.

5

Brief description of the drawings

Fig. 1 shows a typical 3-level wavelet decomposition

of an image using discrete wavelet transform;

Fig. 2 is a block diagram of an embodiment of a

10 processor for reducing video image noise according to the

present invention;

Fig. 3 is a block diagram of an embodiment of a

wavelet domain thresholding function in fig. 2; and

Fig. 4 shows a flowchart of the steps of an embodiment

15 of the method of reducing noise in a video image according

to the present invention.

Detailed description of the invention

20   While this invention is susceptible of embodiments in

many different forms, there are shown in the drawings and

will herein be described in detail, preferred embodiments

of the invention with the understanding that the present

disclosure is to be considered as an exemplification of the

principles of the invention and is not intended to limit
the broad aspects of the invention to the embodiments
illustrated.

5   As noted above, in one embodiment the present
invention provides an improved noise reduction process by
wavelet thresholding, that reduces noise level in video
images and retains as much of the important image features
as possible. In one embodiment, such an improved process
10 first utilizes a discrete wavelet transform to decompose
the image into different resolution levels. Then, a
thresholding function is applied in different resolution
levels with different threshold values to eliminate
insignificant wavelet coefficients which mainly correspond
15 to the noise in the original image. Finally, an inverse
discrete wavelet transform is applied to generate the
noise-reduced video image.

The selection of the threshold values in the second
20 step of the noise reduction procedure above is based on the
relationships between the noise standard deviations of
different decomposition levels in the wavelet domain and
the noise standard deviation of the original image. In one
example, for any fixed discrete wavelet transform: (1) the

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increase, and (2) the noise standard deviations in the

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5 deviation of the original image. This linear dependency

provides a natural choice of the threshold values for

wavelet thresholding. For every discrete wavelet

transform, the noise standard deviations in the wavelet

domain have their unique linear dependency of the noise

10 standard deviation of the original image. Using this linear

dependency in wavelet thresholding is important in

producing artifacts free, natural looking de-noised image,

according to the present invention.

15   Wavelet transformation typically involves decomposing

a signal into a family of functions which are the

translation and dilation of a unique function. In

practice, the wavelet transform is implemented by the

discrete wavelet transform. An example procedure for

20 decomposing an image using discrete wavelet transform is as

follows. A pair of low pass and high pass filters are

chosen, such that the filters exactly halve the frequency

range between themselves. Then, for an image represented

by a two dimensional array of pixel data, the low pass

filter is applied for each row of data to get the low

frequency components of the row, and the resulting signal

is down-sampled by two. Then the high pass filter is

applied for the same row of data to get the high pass

5 components of the row, and the resulting signal is down-

sampled by two and placed to the side of the low pass

components. This procedure is performed for all rows.

Next, a similar filtering procedure is applied for each

column of the intermediate data.

10

Referring to the example in **fig. 1**, a resulting two-

dimensional array 10 of coefficients includes four bands of

data, labeled as ll (low-low), hl (high-low), lh (low-high)

and hh (high-high). While the high pass bands hh, lh and

15 hl include detail information, the low pass band ll still

includes most of the information of the original image.

The ll band can be further decomposed in a similar manner

described above, thereby producing even more subbands. The

decomposing process can be performed to any desired level,

20 resulting in a multi-level or multi-resolution

decomposition of an image. The example in fig. 1 shows a

3-level wavelet decomposition using discrete wavelet

transform. The number in each parenthesis indicates the

level of the decomposition.

Corresponding to the discrete wavelet transform, is the inverse discrete wavelet transform. Just as discrete wavelet transform is used to separate the image into

5 various classes of data, inverse discrete wavelet transform is used to reassemble the various classes of data into a reconstructed image. In an example inverse discrete wavelet transform implementation, a pair of high pass and low pass filters are used. The filtering procedure is the

10 opposite of the corresponding discrete wavelet transforms. Starting from four subband images in the deepest level, first the filters are applied to each subband images column-wise after the column data are up-sampled by two. Next, the filters are applied row-wise to the intermediate

15 data after they have been up-sampled by two. The resulting four signals are added together appropriately. Then a similar procedure proceeds to the next level, until the zero level is reached.

20 Fig. 2 shows a block diagram of an embodiment of a noise reduction processor 20 using discrete wavelet transform and inverse discrete wavelet transform, according to the present invention. The processor inputs are the video image and its noise standard deviation σ. In this

example, it is assumed that the noise standard deviation σ is known and is provided by the system.   Typically, the noise standard deviation σ can be directly estimated from the input image.

5

The example noise reduction processor in fig. 1 comprises a discrete wavelet transform function (dwt) 22, a wavelet domain thresholding function (wdt) 24 and an inverse discrete wavelet transform function (idwt) 26.

10 The input image is transformed in the dwt 22 to decompose the image into K resolution levels, as described above. Preferably, the decomposition level K is set to 4, but other values for k can also be selected.   Although various discrete wavelet transforms can be used, in this example a

15 9/7 wavelet or the 5/3 wavelet are utilized, as presented in the paper: a. Cohen, i. Daubechies, and j.-c. Feauveau, "biorthogonal bases of compactly supported wavelets", communications on pure and applied mathematics, vol. 45, pp. 485-560, 1992.

20

In one example, the low pass filter 22a comprises a 9-tap low pass filter with coefficients (0.026749, -0.016864, -0.078223, 0.266864, 0.602949, 0.266864, -0.078223, -0.016864, 0.026749), and the high pass filter 22b comprises

a 7-tap high pass filter with coefficients (-0.045636,

0.028772, 0.295636, -0.557543, 0.295636, 0.028772, -

0.045636). The 5/3 wavelet has a 5-tap low pass filter

with coefficients (-0.125, 0.250, 0.750, 0.250, -0.125),

5 and a high pass filter with coefficients (0.250, -0.500,

0.250).

After the input image has been decomposed into K

levels by the dwt 22, the wdt 24 applies a thresholding

10 function $\delta_T(w)$ with a different threshold value T to every

wavelet coefficient of every level. This is performed for

all coefficients except for the wavelet coefficients in the

ll band of the deepest level, where the data therein are

simply bypassed. **Fig. 3** shows a block diagram for an

15 example wdt 24 with multiple thresholding function units 30

and a bypass unit 32, wherein each thresholding function is

$\delta_T(w) = \text{sgn}(w)\max(|w|-T,0)$ for a threshold value t. The

function $\text{sgn}(w)$ returns the sign of the wavelet coefficient

value w, and the function $\max(a,b)$ returns the larger one of

20 the two values a and b.

As mentioned in the background section above, an

important step in wavelet based noise reduction is proper

selection of the threshold values. An example of such

selection method according to the present invention is now

described. The values T_i denote the threshold value for

decomposition level i with $i = 1, 2, ..., K$. the threshold values

5 T_i can be represented by example as:

$$T_i = C_i * \sigma \text{ with } i = 1, 2, ..., K,$$

Wherein σ is the noise standard deviation of the input

image, and C_i's are the parameters which are determined by

the discrete wavelet transform that is being used. The C_i

10 parameters characterize the relationship between the noise

distribution in the wavelet domain and the noise

distribution in the spatial domain. If σ_i denotes the

standard deviation of the noise distribution in level i of

the wavelet decomposition, then: $\sigma_i = C_i * \sigma$.

15

The C_i parameters depend only on the specific discrete

wavelet transform. Each discrete wavelet transform has its

own unique set of C_i parameters. For each discrete wavelet

transform, the corresponding C_i parameters need to be

20 calculated only once. Once a discrete wavelet transform's C_i

parameters are known, they can be used in any noise

reduction system that uses this discrete wavelet transform, and need not be recalculated again.

An example method of determining the C_i parameters for a

5 given discrete wavelet transform is now described. Let $f(x_1,x_2)$ denote a constant image, wherein the image has the same gray scale value (e.g., 128) at every pixel (x_1,x_2). Then gaussian noise with zero mean and the standard deviation value σ, are added to the constant image $f(x_1,x_2)$,

10 wherein $f^\sigma(x_1,x_2)$ denotes the resulting noisy image. Next, a discrete wavelet transform is applied to the noisy image $f^\sigma(x_1,x_2)$, wherein $f^\sigma_{HH(i)}(n,m)$ denotes the hh subband image in the decomposition level i (fig. 1). Then, the noise standard deviation σ_i of level i can be computed as:

15
$$\sigma_i = \sqrt{\frac{\sum_{n=1}^{N_i}\sum_{m=1}^{M_i}(f^\sigma_{HH(i)}(n,m)-\mu_i)^2}{N_i \times M_i}}$$

Wherein $N_i \times M_i$ is the size of the subband image $f^\sigma_{HH(i)}(n,m)$, and μ_i is the mean of the subband image $f^\sigma_{HH(i)}(n,m)$, where:

$$\mu_i = \frac{\sum_{n=1}^{N_i}\sum_{m=1}^{M_i}f^\sigma_{HH(i)}(n,m)}{N_i \times M_i}.$$

If σ is varied, and the above procedure is repeated to compute the corresponding σ_i, then by computing the quotient $\dfrac{\sigma_i}{\sigma}$ it can be seen that with the value of σ varying, the

5 quotient $\dfrac{\sigma_i}{\sigma}$ essentially remains constant over. The minor changes in this quotient are caused by the randomness of the added gaussian noise. This essentially constant quotient represents the C_i parameter, i.e., $C_i = \dfrac{\sigma_i}{\sigma}$.

10 For more accuracy, the average of the quotients $\dfrac{\sigma_i}{\sigma}$ for several different σ values can be determined, and that average can be used as the final value of the C_i. This procedure for computing the C_i parameters is repeated for $i = 1,2,...K$ to determine all the C_i's.

15

Two examples of the computed C_i parameters for two discrete wavelet transforms are shown below. The first example is for the 9/7 wavelet mentioned above. For the 9/7 wavelet, with 4 levels of decomposition, $C_1 = 0.50$, $C_2 = 0.28$,

20 $C_3 = 0.13$, and $C_4 = 0.06$. As such, using the 9/7 wavelet for

noise reduction with 4 levels of decomposition, then the threshold values T_i are selected as: $T_1 = 0.50*\sigma$, $T_2 = 0.28*\sigma$, $T_3 = 0.13*\sigma$, and $T_4 = 0.06*\sigma$, wherein σ is the noise standard deviation of the input image.

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The second example is for the 5/3 wavelet mentioned above. For the 5/3 wavelet with 4 levels of decomposition, $C_1 = 0.38$, $C_2 = 0.33$, $C_3 = 0.22$, and $C_4 = 0.13$.

As such, using the 5/3 wavelet for noise reduction with 4

10 levels of decomposition, the threshold values T_i are selected as: $T_1 = 0.38*\sigma$, $T_2 = 0.33*\sigma$, $T_3 = 0.22*\sigma$, and $T_4 = 0.13*\sigma$, wherein σ is the noise standard deviation of the input image.

15 Referring back to system 20 of fig. **2**, the computed threshold values are then applied to the decomposed images by the wdt 24 as described above. After performing wavelet domain thresholding in wdt 24, the idwt 26 applies an inverse discrete wavelet transform to the resulting data

20 from the wdt 24 as described above, to reconstruct the image. The output of the inverse discrete wavelet transform by the idwt 26 represents the output image with reduced noise.

To simplify understanding, fig. 4 shows a flowchart of the steps of an embodiment of the method of reducing noise in a video image according to the present invention. The

5 general method steps are selecting proper threshold values T_i, and then using the threshold values to reduce image noise by wavelet thresholding. Selecting the threshold values includes the steps of: determining the noise standard deviation σ of the input image (step 40);

10 determining the C_i parameters that characterize the relationship between the noise distribution in the wavelet domain and the noise distribution in the spatial domain (step 42); and determining threshold values T_i as: $T_i = C_i * \sigma$ with $i = 1,2,...,K$ (step 44).

15

Using the threshold values to reduce image noise by wavelet thresholding, includes the steps of: decomposing the image into k resolution levels using wavelet transformation (step 46); performing wavelet domain

20 thresholding on the resolution levels using threshold values T_i (step 48); and performing inverse wavelet transformation to the resulting data to reconstruct the image with reduced noise (step 50). An example

implementation of the method in fig. 4 is that shown in figs. 2-3.

The aforementioned systems in figs. 2 and 3 according
5 to the present invention, can be implemented as program
instructions for execution by a processor, as logic
circuits, as asic, as firmware, etc., as is known to those
skilled in the art. Therefore, the present invention is
not limited to the example embodiments described herein.
10

The present invention has been described in
considerable detail with reference to certain preferred
versions thereof; however, other versions are possible.
For example, other frequency transforms can be used which
15 involve mapping of functions of a function space on the
coefficients of basis functions, where the basis functions
have a locality in the frequency spectrum. As such,
functions are decomposed into wave-like components (as e.g.
Cosine, sine or wavelets). The result of the transform are
20 the coefficients of the components (base functions), i.e.
Their share (factor) in the original function. The
transform can be reversed (mostly perfectly or nearly
perfectly) by the sum of the correctly weighted base
functions.

As such, instead of a discrete wavelet transform, other wavelet transforms such as <u>continuous wavelet transform</u>, <u>fast wavelet transform</u>, <u>wavelet packets</u> and

5 <u>complex wavelet transform</u> can be used. Furher, instead of a wavelet transform other transforms such as discrete cosine transforms may be utilized. Therefore, the spirit and scope of the appended claims should not be limited to the description of the preferred versions contained herein.